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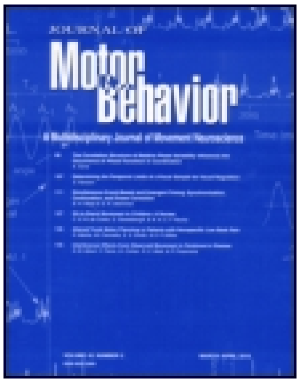

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ABSTRACT. Catching a ball requires that information be available close to the catch but early enough for prospective or corrective control. In the present experiment, 6 participants were asked to throw and catch a ball continuously for 1 min while wearing liquid-crystal goggles that restricted viewing to specific amounts of time at specific intervals. Participants were free to select the information by varying the frequency and phasing of throwing relative to the goggles. Video analysis revealed that they elected a frequency of throwing that matched the goggle frequency and chose to view the ball at or around its zenith. Earlier portions of the ball's trajectory were viewed as the goggle frequency increased. Despite variations in the viewing location, participants elected to view the ball on average 365 ms before the catch. Analysis of the hand's trajectory further revealed that the time interval (M = 82 ms) between the ball's zenith and the initiation of the final motion of the hand toward the catch did not vary as a function of the frequency of throwing. The authors conclude that the timing constraints imposed by the hand's movement are the basis for the selection of information for catching.

Key words: attention, catching, information

Controlling an interceptive act requires that information be made available regarding the approaches of both the object and the actor toward the point and time of interception. Catching a ball is a prototypical example of such an act. As the ball approaches, one must use information about the ball's trajectory to guide the hand to the appropriate place and time of contact. The questions of what that information is and how it is used in controlling the catching movements are, therefore, central to an understanding of interceptive control.

Information for Catching

Numerous studies have been directed at identifying the information for catching. The predominant paradigm has been one in which the experimenter selectively eliminates a potentially relevant form of information and observes the resulting deficits in performance. One particularly viable form of information is the pattern of optical expansion associated with an approaching ball. Those optical patterns can be shown to specify the time to contact with the point of observation (e.g., Lee, 1976). Research showing that observers are sensitive to that variable has provided support for the hypothesis that observers use that information in catching (Bootsma & Peper, 1992; Savelsbergh, Whiting, & Bootsma, 1991; Savelsbergh, Whiting, Pijpers, & Van Santvoord, 1993), although that hypothesis is not without its critics (Wann, 1996; see also replies by Bootsma, Fayt, Zaal, & Laurent, 1997, and Tresilian, 1997). Additional optical variables from the ball and its surround have been identified that also appear to be used in catching (Michaels & Oudejans, 1992; Montagne & Laurent, 1994; Peper, Bootsma, Mestre, & Bakker, 1994; Rosengren, Pick, & von Hofsten, 1988; Savelsbergh & Whiting, 1988; Sharp & Whiting, 1974; Van der Kamp, Savelsbergh, & Smeets, 1997; Whiting, 1968, 1970; Whiting, Gill, & Stephenson, 1970; Whiting, Savelsbergh, & Faber, 1988; Whiting & Sharp, 1974). Likewise, proprioceptive information about the hand has been shown to be important for a successful catch (Fischman & Schneider, 1985; Rosengren et al., 1988; Savelsbergh & Whiting, 1988; Smyth, 1986; Smyth & Marriott, 1982; Whiting, 1986; Whiting et al., 1988).

The aforementioned research has demonstrated that, although there are a number of candidate information variables for controlling an interceptive act, no one variable can yet be identified as critical. The possibility of multiple types

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of information may be related to the multiple kinematic phases of the hand during the catch (Alderson, Sully, & Sully, 1974; Beek & Beek, 1988; Fischman, 1986; Fischman & Schneider, 1985; Laurent, Montagne, & Savelsbergh, 1994; Peper et al., 1994; Savelsbergh et al., 1993; Smyth, 1986; Van der Kamp et al., 1997). Different stages of the interceptive act may be controlled by different forms of information. In the present experiment, those lines of investigation were continued. Participants were forced to actively select the information for sustained rhythmic catching. In the analysis, we focused on identifying the participants' selection criterion and investigating the way that that selection was related to the kinematics of the hand.

Information Selection in Catching

If an individual is to catch a ball, information must be available to his visual perceptual system. Although information from the ball's trajectory is critical for a successful catch, continuous visual tracking along the entire trajectory (keeping one's eye on the ball) is not necessary. Participants are able to catch successfully a ball that is illuminated for only a portion of its trajectory (Savelsbergh et al., 1993; Sharp & Whiting, 1974; Whiting, 1968, 1970; Whiting et al., 1970; Whiting & Sharp, 1974). Individuals must, therefore, actively select information from the ball's trajectory at some intermediate point or time. In fact, it has been shown that in a continuous catching task, selectively illuminating the ball in the center portion of its flight did not produce a significant deficit in the performance of experienced individuals when compared with their perform-ance during full illumination (Whiting, 1968). Selectively illuminating only the beginning or end of the trajectory, however, decreased significantly the performance of those participants. It remains unclear whether individuals select information around a particular spatial region of the trajectory (such as the zenith) or at a particular time (perhaps some number of reaction times before the catch).

In some studies on catching a ball that is projected toward the actor, the authors have concluded that viewing the ball at a particular time may be preferred (Sharp & Whiting, 1974, 1975; Whiting & Sharp, 1974). In those studies, balls were projected at the observer along a parabolic flight path in a darkened room. The observer's task was to catch as many of the balls as possible. The room was illuminated for varying amounts of time at varying locations along the ball's trajectory. The results of those studies indicate that the amount of time that has elapsed between viewing of the ball and the catch may be most relevant. Performance (indexed by the number of successful catches) was an inverted U-shaped function of that time: Performance was worst at extremely short or long intervals and was maximized at some intermediate interval. In another study, the participants controlled when the ball would be illuminated, but it was not possible to identify a critical time at which the ball must be viewed (Whiting, 1970). Although it was concluded in those studies that participants preferred to view the ball at a particular point in time, the length of the flight path was not varied within an experiment, leading to a covariation between the position and the time at which the ball was viewed.

Van Santvoord and Beek (1994) investigated information selection during catching in their analysis of the visual control of the three-ball cascade juggle. Because more than one ball is being controlled during juggling, continuous visual tracking is impossible. To identify the portion of the ball's flight that is selected by the juggler as being the most informative, Van Santvoord and Beek exploited in their method the fact that the juggler controls the timing of both throwing and catching. Portions of the ball's flight were occluded, but the jugglers were allowed to choose which portion was visible and which portion was occluded. Intermediate-level jugglers performed a three-ball cascade while wearing liquid-crystal (LC) goggles that allowed viewing only during intermittent intervals. The open-window interval decreased over the course of each trial. Van Santvoord and Beek held constant the frequency of occurrence of the midpoint of the viewing window by manipulating symmetrically the opening and closing times of the goggles. The jugglers were allowed to juggle freely. The investigators used film analysis to determine where, relative to the zenith, the jugglers chose to place the viewing window on each cycle.

Van Santvoord and Beek (1994) predicted that observers would prefer to view the portion of the ball's flight around the zenith (for additional discussions relating to the potential importance of optical variables sampled at the zenith, see Todd, 1981; Watson, Banks, von Hofsten, & Royden, 1992). That prediction was motivated in part by Austin's (1976) demonstration that juggling could be performed successfully while jugglers viewed as little as 1 in. (2.5 cm) of the ball's flight around the zenith (50–80 ms) and by juggling instructors' instruction to "look at the zenith." One participant's results conformed to those expectations, whereas the data from the other 2 participants showed evidence of such phasing only during some trials. Although a precise preferred viewing location could not be identified, there was evidence across participants that the jugglers phased their actions so as to view the ball around the zenith. By not varying frequency, however, it was not possible to distinguish between temporal and spatial constraints on information selection in the studies of Van Santvoord and Beek (1994).

Overview

We designed the present experiment to test whether participants, when forced to choose, select information by electing to view the ball at either a particular location or a particular time along its trajectory. We used a paradigm similar to Van Santvoord and Beek's (1994), which included variations in the frequency of the goggles. Observers threw and caught a single ball continuously with one hand while wearing LC goggles that allowed viewing for specified amounts of time and at specified frequencies. We used manipulation of the frequency of the goggles to test whether participants preferred to view the ball at a particular location or at a particular time relative to the throw or catch. Limiting the viewing window to as little as 100 ms in some trials (in contrast to the more than 1 s observed by Whiting, 1970), allowed for a better determination of a critical time or location for viewing the ball than was previously possible. We conducted analyses of the hand's trajectory to examine if the selection criteria were in any way related to the kinematic portrait of the hand.

Method

Participants

Six men participated in this study. One was eliminated during training after he reported that he closed his eyes to avoid the distraction from the goggles and that he accommodated for that lack of vision with throws of extremely small amplitude. All the remaining 5 participants (mean age = 29.2 years, range = 24–34 years) were right-handed, naive to the experimental task, and unable to throw and catch a single ball continuously without vision.[1]

Design

Participants threw and caught a ball continuously with their right hand. The vertical positions of the ball and the participants' right wrists were recorded from video. During the performance of the task, participants wore LC goggles that would intermittently occlude their view of the ball. The independent variables were the size and frequency of the viewing window. There were three lengths of the viewing window (.1-cycle period, .125-cycle period, and .15-cycle period) and three frequencies (1.0, 0.769, and 0.625 Hz). The three levels of viewing window length crossed with the three levels of frequency resulted in the following viewing windows: 100, 125, and 150 ms at 1.0 Hz; 130, 162.5, and 185 ms at 0.769 Hz; and 160, 200, and 240 ms at 0.625 Hz.

Apparatus

Participants were videotaped while they threw and caught a 130-g white ball (a juggling "stage ball") that was 7.3 cm in diameter. A circular marker (2 cm in diameter) of white paper on a black-paper background was attached to the participant's right wrist with a Velcro strap. The walls in front of and to the right of the participant were covered with black fabric. White markers, hung behind and out of the view of the participant, provided a reference for the video analysis.

Each participant wore a pair of LC goggles (Milgram, 1987); we used the goggles to manipulate visibility. The goggles were attached to an IBM PC 386 computer that controlled whether the goggles were open or closed; the term *open* indicates that the LC glass was transparent and that vision was allowed, whereas the term *closed* indicates that the liquid-crystal glass was opaque and that vision was occluded. For a given trial, the goggles were set to start with an open window of .80 cycle for the first cycle. The window length would then decrease by a constant amount on every cycle until the proper window length for that condition was reached. The period of decreasing viewing time lasted for 20 s for every trial. A small indicator light, connected to the goggles, was placed out of the participants' view but within view of the video camera. We used it to provide a signal on the videotape that the goggles were open or closed.

A video camera (JVC SVHS camcorder GF-S1000H) was placed approximately 4 m to the left of the participant at approximately shoulder height. We increased vertical spatial resolution by recording with the video camera on its side. The frame rate of the video camera was 50 Hz, resulting in a temporal resolution and absolute error of 20 ms. Lighting provided by a stage light placed next to the camera ensured that the lighting angle was as close as possible to the camera angle. All the other lights in the room were turned off, and opaque curtains covered the windows.

Procedure

The entire procedure consisted of a pretest for preferred frequency, a training session, and an experimental session. Only the data from the experimental session were analyzed. Before the training, the participant was asked to throw and catch the ball rhythmically for 1 min while the experimenters counted the number of complete cycles. That 1-min timing was repeated three times, and the mean number of cycles was used as a measure of the participant's preferred frequency of throwing. During that pretest, the participant wore the goggles, although they remained open.

We began the training by introducing the participant to the task with a relatively easy set of task constraints. The goggles were set to open at a frequency corresponding to the participant's preferred frequency of throwing. As described above, the goggles would start with an initial window of .80 cycle and decrease to .25 cycle over the first 20 s of the trial. The goggles would then open and close continuously at that rhythm for 40 s. The only instructions to the participants were to throw and catch the ball continuously in whatever manner was required to perform the task. The participants were not instructed to throw at any particular frequency or to any particular height. For each training condition, there was a criterion of two consecutive successful trials (where *success* was defined as not dropping the ball) before progressing. After reaching criterion on that condition, the participants were introduced to each of the nine experimental conditions in a random order. As in the initial condition, the goggles would start with an initial window length of .80 cycle and decrease to the specified length over the first 20 s. The goggles would then open and close continuously at that rhythm for 40 s. Training was complete when participants met the criterion of two consecutive successful trials in each of the nine conditions. Participants were allowed to request a rest between trials.

The experimental session was run on a subsequent day. The experimental session was identical to the training session, with the following exceptions. In the experimental session, participants had to complete two successful trials in each of the nine conditions, although the two trials did not have to be consecutive. The conditions were randomly presented in two blocks of nine. Successful completion of each condition was required before progressing to the subsequent condition.

Data Reduction and Analysis

The horizontal and vertical positions of the ball and the wrist during the stable 40-s period of each trial were recorded from each frame of the videotapes. Only the vertical positions were analyzed. A sample time series from one trial for both the ball and hand is depicted in Figure 1. The opening and closing times of the goggles were recorded by visual inspection of the indicator light on the videotape. The *opening time* was defined as the first video frame on which the indicator light was on, and the *closing time* was defined as the first video frame on which the indicator light was off. The maximal error in defining those times was one frame, or 20 ms. Analysis of the times of opening and closing revealed that the mean recorded frequencies (0.996, 0.768, and 0.623 Hz, for the 1.0-, 0.769-, and 0.625-Hz conditions, respectively) and the mean recorded window lengths (.1-cycle period, .124-cycle period, and .15-cycle period, for the .1-, .125-, and .15-cycle-period conditions, respectively) were close to the specified values.

To determine the moments (in milliseconds) of each throw, catch, and zenith of the ball as well as the moments (in ms) when the direction of wrist acceleration shifted, we analyzed the vertical-position time series of the ball and wrist. The absolute error in calculating those moments was one frame, or 20 ms. The zenith of the ball's trajectory, z_i, was defined as the moment of maximal vertical position, where *i* refers to cycle number. We used the moment of the ball's maximal upward velocity to define the moment of throwing, t_i, and the frame following the maximal downward velocity to define the moment of catching, c_i. Ball frequency was calculated as $[1000(z_i - z_{i-1})]^{-1}$. The mean cycle-by-cycle frequency per trial was used as a measure of ball frequency, ω_{ave}. Using the convention of Van Santvoord and Beek (1994), we defined the relative phasing, ϕ_i (rad), of the ball's zenith relative to the midpoint of the viewing window of the goggles, w_i, as

$$\phi_i = \frac{z_i - w_i}{w_i - w_{i-1}} \times 2\pi. \tag{1}$$

Here, $\phi_i < 0$ indicates that z_i occurred after w_i; $\phi_i > 0$ indicates that z_i occurred before w_i; and ϕ_i is a measure of the

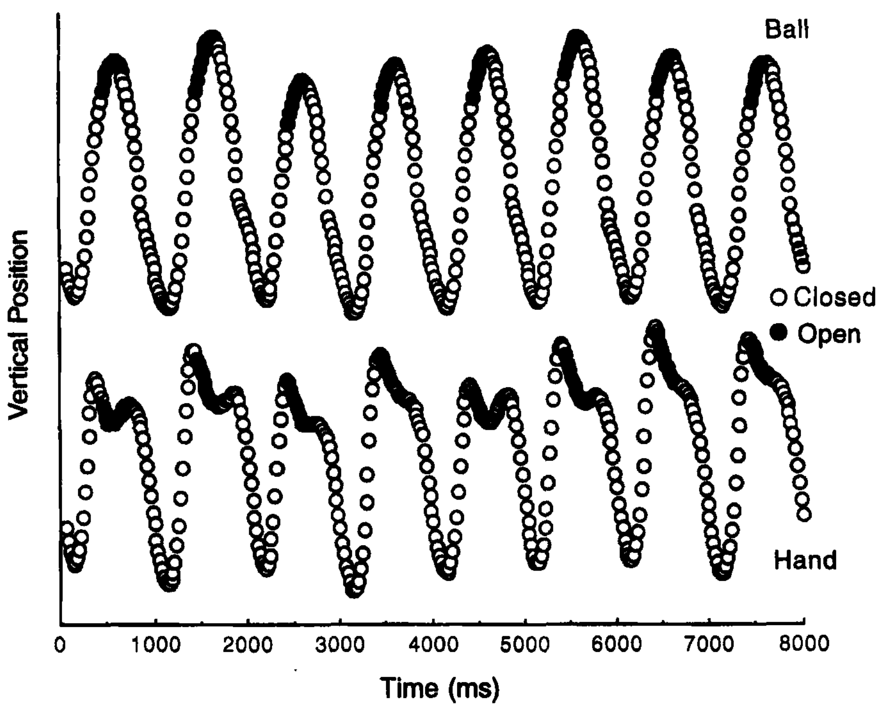

FIGURE 1. Sample time series of the vertical positions of the ball (upper series) and hand (lower series) during 8 s of sustained rhythmic throwing and catching. Filled circles indicate when the goggles were open and the ball was in view. For purposes of illustration, the two time series have been displaced vertically.

spatial location along the ball's trajectory at which the participant elected to view the ball on a particular cycle.

Results

Ball Frequency

The mean preferred frequency of throwing during the pretest was 0.934 Hz. A repeated measures analysis of variance (ANOVA) of ω_{ave} as a function of goggle frequency and window length was conducted. There was a significant effect of goggle frequency on ω_{ave}, $F(2, 8) = 6785.55$, $p < .0001$, but there was no significant effect of window length; nor was there a significant interaction between the two independent variables. Participants elected a ω_{ave} that corresponded to the frequency of the goggles (ω_{ave} = 0.994, 0.767, and 0.627 Hz for goggle frequencies of 1.0, 0.769, and 0.625 Hz, respectively). Such a strategy of throwing the ball at the frequency of the goggles would be required if the participant were to view the ball at the same point in its cycle, either spatial or temporal, on a given trial.

Relative Phase and Its Stability

To test the hypothesis that individuals prefer to view the ball at a particular location along its trajectory, we calculated ϕ_i for each cycle and averaged ϕ_i across cycles in a trial to obtain a measure of mean relative phase, ϕ_{ave}. The resulting ϕ_{ave} in each of the nine conditions are depicted in Figure 2. Consistent with the results of Van Santvoord and Beek (1994), there was a tendency to view the ball in the region around the zenith, $\phi = 0$. In fact, in the mean across participants, the zenith tended to occur within the open window, although there were a number of individual trials in which the participant performed the task successfully while the ball's zenith was outside of the viewing window. A repeated measures ANOVA was conducted on ϕ_{ave} as a function of goggle frequency and window length. As depicted in Figure 2, there was a significant effect of goggle frequency on ϕ_{ave}, $F(2, 8) = 6.43$, $p < .05$. An increase in goggle frequency was accompanied by a tendency to view the ball earlier in its cycle. Only at the slowest frequency was there a mean tendency to view the portion of the cycle following the zenith. There was no significant effect of window size on ϕ_{ave}, $F(2, 8) = 1.51$, $p > .25$, nor was there an interaction between the two independent variables, $F(4, 16) = 1.2$, $p > .30$. The participants seemed to prefer to see the ball in some region around the zenith but not at a particular location.

The stability of ϕ_{ave} (i.e., of the relative phasing between the ball's zenith and the midpoint of the viewing window) was indexed by the standard deviation of ϕ_i ($SD\phi$) for a given trial. Those results are shown in Figure 3. A repeated measures ANOVA was conducted on $SD\phi$ as a function of goggle frequency and window length. In contrast to the results for ϕ_{ave}, there was no effect of frequency on $SD\phi$, $F(2, 8) = 2.17$, $p > .15$. Although participants chose different phase relations across goggle frequencies, no one value was significantly more variable than another. There was, however, a significant effect of window length on $SD\phi$, where variability increased with greater viewing window lengths, $F(2, 8) = 16.75$, $p < .005$. There was no significant interaction between the two independent variables, $F(4, 16) = 0.3$, $p > .85$.

Timing the Selection of Information

To test the hypothesis that participants phased their behavior to the goggles to view the ball at a particular time relative to the catch, we subtracted the times of the midpoints of the corresponding viewing windows, w_i, from time of the catch, c_i, to obtain a measure of the time intervals. The positive $c_i - w_i$ intervals indicate that the catch occurred after the midpoint of the viewing window. The mean of $c_i - w_i$ across a trial was used as a measure of mean time interval between viewing and catching, $(c - w)_{ave}$. The effects of frequency and window length on $(c - w)_{ave}$ for all 5 participants (panels

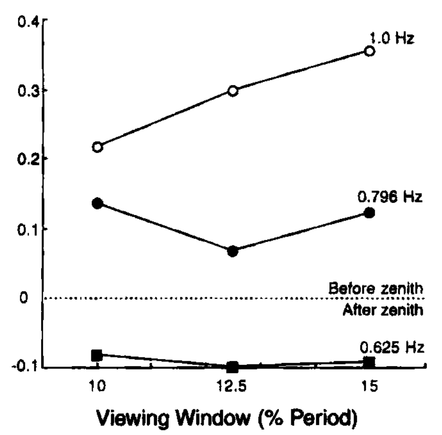

FIGURE 2. Mean relative phase, ϕ_{ave}, as a function of goggle frequency and viewing window length.

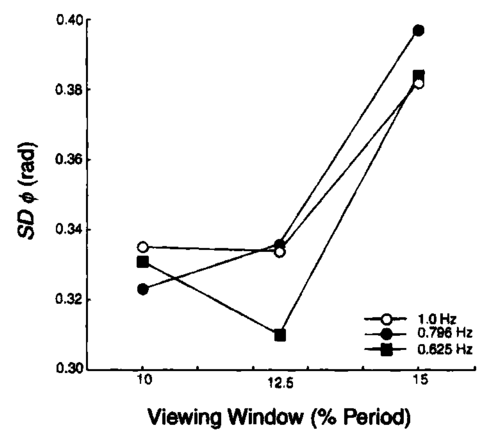

FIGURE 3. Standard deviation of ϕ ($SD\phi$) as a function of goggle frequency and viewing window length.

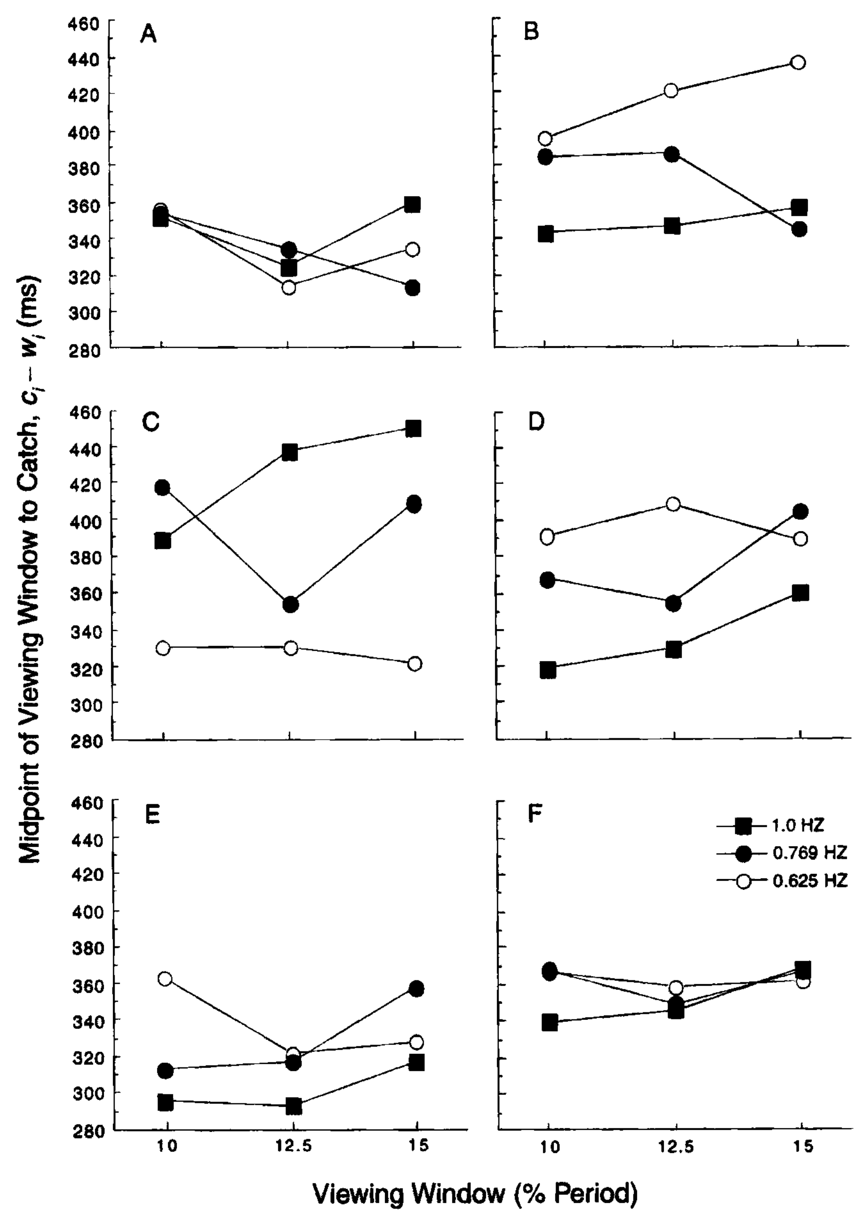

FIGURE 4. Time intervals between viewing and catching the ball. The data for each participant are shown in panels **A–E**, and the group means are depicted in panel **F**.

A–E) and for the group (panel F) are shown in Figure 4. A repeated measures ANOVA was conducted on $(c - w)_{ave}$ as a function of goggle frequency and the length of the viewing window. None of the effects was significant: frequency, $F(2, 8) = 0.15$, $p > .85$; viewing window length, $F(2, 8) = 2.25$, $p > .15$; and interaction, $F(4, 16) = 1.02$, $p > .40$. As can be seen in Figure 4, the mean intervals in each condition were around 365 ms. The entire range in condition means was only 25 ms. The mean time interval for each of the individual participants was within 35 ms of the group mean: 342, 379, 382, 369, and 333 ms, with standard deviations across conditions of 21, 34, 50, 32, and 26 ms, respectively. The mean standard deviation within a single trial was 74 ms, with a range across all conditions of all participants of 45–149 ms. Participants seemed to elect to view the ball at a particular time, around 365 ms, before the catch.

Because we manipulated the size of the viewing window by varying both the opening and closing times simultaneously, the constant interval between the midpoint of the viewing window and the catch was not accompanied by constant intervals between the opening and closing of the goggles and the catch. A repeated measures ANOVA showed a significant effect of window length on both intervals: open to catch, $F(2, 8) = 11.756$, $p < .005$; closed to catch, $F(2, 8) = 7.656$, $p < .05$. Therefore, participants seemed to time their actions to the viewing window as a whole rather than to the discrete events of the opening and closing of the goggles.

Hand Trajectory

A typical portion of the hand's trajectory is depicted in Figures 1 and 5. During the loaded portion of the cycle (when the ball was in the hand), the hand tended to follow a relatively smooth sinusoidal trajectory. That trajectory continued through the throw to the point at which the hand reached its maximal height and began to move downward. Shortly after the hand reached its highest point, the previously sinusoidal path was broken by an inflection where the hand was accelerated briefly upward (see Figure 5 for typical position and acceleration profiles). Although shown as a reversal of motion in Figures 1 and 5, on some cycles there was a stopping of the hand or just a temporary slowing of the downward velocity. Across all trials, the hand's trajectory exhibited that *inflection* (defined as a positive vertical acceleration followed by a negative vertical acceleration) on 98.26% of the cycles. A repeated measures ANOVA on those values as a function of goggle frequency and the length of the viewing window revealed that the portion of cycles with an inflection did not vary significantly across conditions. The mean times of those accelerations are depicted with triangles in Figure 6. Note that the catch did not tend to occur during the inflection period but, rather, at some time after the downward acceleration had resumed.

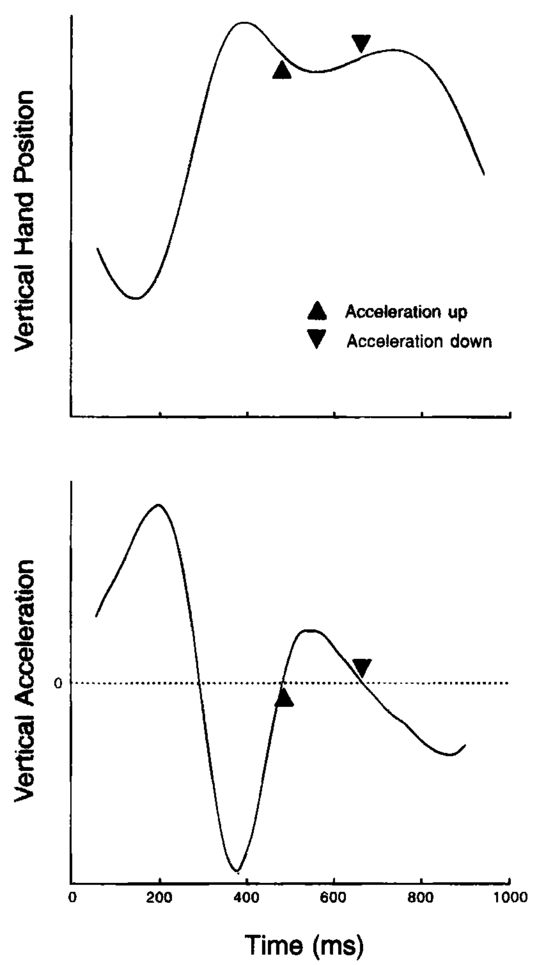

FIGURE 5. Sample cycle of the hand's vertical position **(top panel)** and acceleration **(bottom panel)**. The throw occurred toward the beginning of the cycle when the hand was moving upward with its maximal acceleration. After the throw, the hand continued to move upward to its maximum position. Shortly after passing through its maximum position, the hand's downward motion was broken by an inflection where it was accelerated briefly upward. The acceleration points that characterize the inflection in the hand's trajectory are indicated with triangles in both panels. Following that inflection, the hand continued to move down toward the catch.

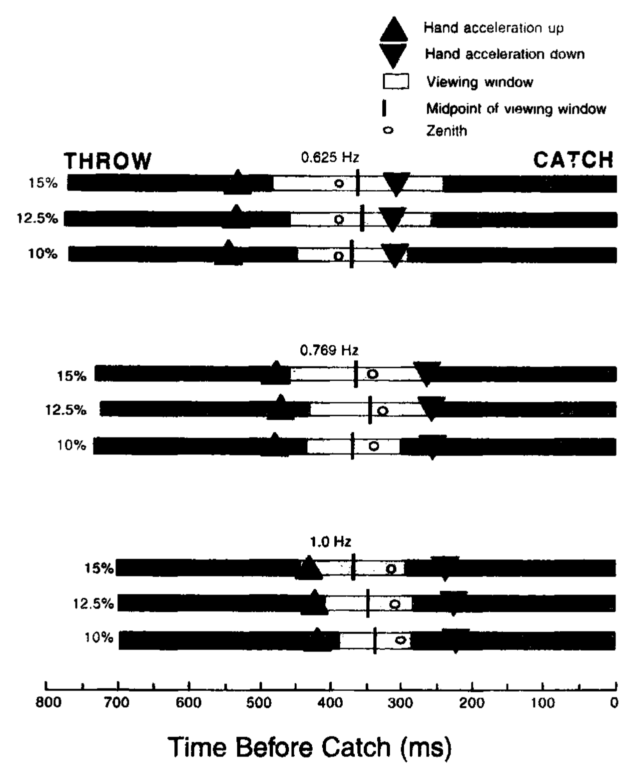

FIGURE 6. Mean times of the various ball and hand events that occurred between the throw **(left)** and the catch (**right**) in each of the nine conditions. For the ball, those events were the time during which the ball was in view, the midpoint of the viewing window, and the moment of the ball's zenith. For the hand, the events were the throw, the catch, and the two acceleration points after the hand reached its maximum position where the hand was accelerated upward (leftmost triangle) and where the hand was accelerated downward toward the catch (rightmost triangle).

The inflection in the hand's trajectory always occurred around the time when the goggles were open and the ball was in view. The actor may have been using information about the ball's trajectory to control the hand's acceleration pattern in order to prepare for the catch. To investigate that possibility, we calculated the times of each relevant ball and hand event for the unloaded portion (between the throw and the catch) of each cycle. For the ball, those were the moments at which the goggles opened and closed as well as the midpoint of the viewing window and the zenith of the ball's flight. For the hand, the relevant events were the moments at which the hand was accelerated upward and accelerated downward after the hand had reached its maximal position. The mean times of each event, relative to the catch, are depicted in Figure 6.

It can be seen in Figure 6 that the midpoint of the viewing window and the ball's zenith both occurred after the first acceleration point (where the hand was accelerated upward) but before the second (where the hand was accelerated downward toward the catch). Further, the first acceleration point tended to occur before ($M = 38$ ms) the opening of the goggles, indicating that the control of that point was likely independent of vision. By contrast, participants could control the second acceleration point by using the information about the ball that was detected by visual perception. The interval between the ball's zenith and the initiation of the downward acceleration was calculated. That analysis revealed a mean interval of 82 ms between the zenith of the ball's flight trajectory and the initiation of the downward acceleration of the hand. That interval was constant in the sense that there was no significant effect of either frequency or window length; nor was there an interaction between the two independent variables. The range of condition means was 12 ms. The individual participant means were 45, 72, 126, 82, and 86 ms, with standard deviations across conditions of 12, 31, 11, 15, and 18 ms, respectively. Although there was variability across participants in the timing of the catch, there was little variability in each participant's behavior across conditions. The participants may have been using the time of the ball's zenith to time the initiation of the catch.

Discussion

Participants in the present experiment threw and caught a ball continuously with their right hands while wearing LC goggles that restricted their viewing to specified amounts of time at specified intervals. When the goggles were closed, there was no information available to the visual perceptual system about the ball's flight. On some trials, the goggles were open for as little as 100 ms, severely limiting the viewing time. The participants were allowed to throw freely, at whatever frequency and phase relative to the goggles that they preferred. By constraining the viewing time in that manner, we could determine whether there were any regularities in what the participants elected to view. Such regularities should help to identify the critical or preferred information for catching and, perhaps, interceptive acts in general.

Acting to Perceive

The results showed that participants threw the ball at a frequency that matched the frequency of the goggles. The participants needed such a strategy to view the ball either at a constant location along its trajectory or at a constant time relative to the catch. It is commonly accepted that behavior such as catching is guided by perception, but the present results go further and provide an example of the added claim of Gibson (1979) that "we must perceive in order to move, but we must also move in order to perceive" (p. 223). The participants in the present experiment acted in ways that would make the requisite information available. The frequency of the goggles imposed a temporal scale on the visible environment. By throwing the ball at a frequency that matched the frequency of the goggles, the participant arranged the event so that all the components (the throwing, catching, ball flight, and perceiving) were operating at the same temporal scale, the frequency of the goggles. The act of frequency coupling observed here allowed the participant to perceive the required properties for sustained rhythmic throwing. The participants acted in order to perceive.

The Information for Catching

Across conditions, there was a tendency for participants to view the ball at or around the zenith of its flight trajectory. The precise location varied with manipulations of the goggle frequency, however; the ball was viewed progressively earlier in its trajectory as frequency increased. In fact, the participants often elected to view the ball moving up toward the zenith rather than down toward the catching hand. Those who have suggested that the criterion for selecting information in such a task is spatial have predicted that the segment of the ball's flight immediately following the zenith would be preferred (Todd, 1981; Van Santvoord & Beek, 1994; Watson et al., 1992). The logic was that the optical transformations associated with a falling ball would be informative about the future times of contact with various positions along the flight path (see, e.g., Bootsma & Oudejans, 1993; Lee, Young, Reddish, Lough, & Clayton, 1983; Todd, 1981; Watson et al., 1992). By electing to view the ball immediately following the zenith, participants could make that optical information available as soon as possible and ensure that a maximum amount of time was available for corrections of the hand's movements. Further, with respect to defining the selected information, the optical transformations across cycles will be equivalent at a particular relative phase. That suggests not only that the participant's selection criterion is not spatial but that the critical or preferred information is not a particular optical transformation.

An analysis of the time at which participants chose to view the ball revealed a mean time of 365 ms between viewing and catching the ball. Those results are consistent with the findings of Whiting and Sharp (1974); in that study, catching performance was maximized when the midpoint of the viewing window occurred about 325 ms before the catch.[2] That there should be a critical time of about 300 ms prior to catching for the selection of information has been discussed elsewhere and has been the basis for the nonlinear retinal expansion rate for an approaching object (Lee, 1980; Savelsbergh et al., 1993). The present results are suggestive of two hypotheses, one regarding the nature of the information for this task and one regarding the basis for that selection criterion. Although the participants organized their behavior around a time interval that was, for the present purposes, indexed by a single instant in time (365 ms), it should be noted that they actually viewed the ball across a segment of time that lasted from 100 to 240 ms. Thus, the relevant variables existed over a time window around that instant. The fact that the participants elected to view the ball either before or following the zenith indicates that the sampled information may be about the ball's zenith. The optical transformations associated with the ball's flight on either side of the zenith could specify both the time at which the ball reached the zenith and the time the ball will reach the zenith. Although it was not tested here, those results suggest that the timing of the ball's zenith and the associated information could be critical event properties for the control of sustained throwing and catching.

A second hypothesis suggested by the constant timing of the viewing window is that the selection of information may be related to the time constraints on performing certain actions required for catching the ball. Previous research has shown that there are multiple kinematic phases in the act of catching (Alderson et al., 1974; Beek & Beek, 1988; Fischman, 1986; Fischman & Schneider, 1985; Laurent et al., 1994; Peper et al., 1994; Savelsbergh et al., 1993; Smyth, 1986; Van der Kamp et al., 1997). If any of those submovements or phases requires some information, then presumably that information should be made available before its initiation. As was presented earlier, the information for this particular task may be about the time of the ball's zenith. An analysis of the hand's trajectory revealed that the relatively sinusoidal path of the hand was broken by an upward and then a downward acceleration around the time when the goggles were open. The downward acceleration, which occurred after the ball was in view, tended to follow 82 ms after the ball's zenith (although there was between-participants variability in the particular time chosen). Because that acceleration marks the beginning of the hand's motion toward the catch, those results suggest that one may use the information regarding the time of the ball's zenith to initiate the catch.

Discrete Information in a Continuous Act

The indication that one selects information to initiate a particular kinematic phase of the catch, along with our method of imposing a discrete component on a continuous act, should not be taken to suggest that the control of catching is necessarily discrete. In fact, the movement patterns observed in the present experiment are also consistent with a continuous model of control in catching (e.g., Michaels & Oudejans, 1992; Peper et al., 1994). According to such a position, actions are controlled (i.e., prepared, initiated, and executed) from moment to moment on the basis of the currently available information. Although in the present analysis we focused on the timing of the initiation of one phase of the catch, it should be highlighted that that event was not insular.

The nature of both the task and the data are consistent with a continuous form of control. Given the coupling between the throwing and goggle frequencies, the participants presumably had information (from the previous cycles) about when the goggles would open. Even when the ball was not in view, the participant was controlling the hand's movements on the basis of previously obtained information. By coupling the ball and goggle events in that fashion, the participant could ensure that the ball would be at a particular place and time for viewing. Simultaneously, the participant was also controlling the accelerations of the hand that occurred prior to viewing (perhaps on the basis of haptic information from the throw), which could be interpreted as serving to prepare the hand for the next phase of the catch. It should be highlighted that the 82-ms time lag between the zenith and the final acceleration of the hand was relatively short. That time lag could indicate that the participant prepared for that phase before viewing the ball and then used whatever information was available across the entire viewing window to control the unfolding act. That conception contrasts with one where the individual waits for the necessary information, generates a predicted ball trajectory, plans an appropriate act, and then initiates that act.

All of those observed behavioral patterns are consistent with a model of continuous control where individuals control actions on a moment-to-moment basis by using currently available information. Control of an act such as catching, with its multiple kinematic phases, can still be thought of as continuous when the execution of one phase also serves as the preparation for another. Likewise, the fact that the viewing was discrete need not preclude the possibility that continuous control occurs when information that is obtained from previous cycles or from other perceptual systems, such as haptic perception, can be used. We do not wish to suggest here that our data provide a test of a continuous model of control; the experiment was a test of how individuals select information. Rather, we wish to point out that, despite the discrete viewing and the focus on a particular kinematic phase, our results remain consistent with a continuous model of control.

Haptic Perception

Although we used viewing constraints in the present experiment to investigate the information for controlling an interceptive act, it would be premature to conclude that vision is all that is being used, especially in the present task. As in juggling, individuals who are sustaining rhythmic throwing and catching have access to more information than just the optical information from the ball's flight. By throwing the ball to themselves, the participants presumably obtain some information from the haptic perceptual system regarding the success of the throw. That information could also be used in the control of the interceptive act. For example, one may control the hand's trajectory before viewing the ball by using information from the throw that could be detected by haptic perception. As can be seen in Figures 1 and 5, there are a number of hand events that occur before viewing the ball. The hand continues to move upward following the throw, reverses course, and then is accelerated upward again before the opening of the goggles. In principle, one could control any or all of those events by using the haptic perception of the throw. Even the subsequent information detected by vision may not be completely independent of any previously obtained haptic perceptions. Rather, vision may update the haptic perception of the ball's flight. Such issues could be the focus of future research.

Conclusions

In the present task, when participants were forced to select what to attend to visually but were allowed the freedom to select what to view, their selection appeared to be made on the basis of timing rather than spatial constraints. We hypothesized that that timing characteristic of information selection may be related to the timing constraints inherent in catching. An analysis of the hand's trajectory revealed a constant time interval between the zenith of the ball's trajectory and the initiation of the catch. It is possible, therefore, that the participants used time-to-contact information about the ball's zenith to time the catch appropriately. The selection of information for catching appears to be made on the basis of the timing constraints of the catching movements. In the context of a perceiving–acting cycle, the present results show that perception informs action but that action also serves to make the requisite information available.

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NOTES

1. Professional jugglers who can juggle three balls blindfolded report that, contrary to expectations, it is more difficult to throw one ball continuously without vision than it is to juggle three balls without vision.

2. For purposes of comparison, we converted the results of Whiting and Sharp (1974) so that they would be more similar to the present results by adding the constant 125-ms latency period and 40-ms half viewing period that were reported in that article.

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